Fast and accurate low-coherence interferometric measurements of fiber Bragg grating dispersion and reflectance

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Abstract*:* We demonstrate fast and accurate measurements of fiber Bragg grating dispersion and spectral reflectance using low-coherence interferometry. Both dispersion and spectral reflectance are obtained in less than 60 seconds, rendering the results immune to errors caused by temperature variations and instrumental drift. To examine the accuracy of the low-coherence technique, we compare the results with independent measurements and demonstrate an agreement better than 1.5 ps for dispersion and 25 pm for spectral reflectance wavelength.

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1. Introduction

Low-coherence interferometry has been used to measure the dispersion of many optical components, including optical fibers [1], mirrors, prisms, [2] and arrayed waveguide gratings [3]. We show that low-coherence interferometry can also be used to determine the dispersion and spectral reflectance of wavelength-selective reflectors, such as fiber Bragg gratings (FBGs). To illustrate the accuracy of this technique, we compare our results with the dispersion and spectral reflectance obtained from independent measurements. A key advantage is that the low-coherence measurement can be made in less than one second, and dispersion and spectral reflectance can be obtained from the interferogram in less than one

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minute of processing time, compared with the conventional modulation-phase shift and tunable laser measurements, which can take several hours [4,5]. The rapidity of the low-coherence measurement renders the results immune to errors caused by temperature variations and instrumental drift.

2. Description of measurement

A diagram of the low-coherence interferometer is shown in Fig. 1. An erbium superfluorescent fiber source (SFS) is coupled to a fiber interferometer. The FBG is spliced into the test arm of the fiber interferometer, and the reference arm contains an air path so that the total optical path difference (OPD) of the interferometer can be varied. To optimize fringe visibility, a polarization controller is included in the reference arm to match the polarization states of the test and reference arms. An air-path interferometer incorporating a single-frequency 633 nm HeNe laser monitors the position of the reference arm mirror. A zero-crossing circuit determines the positive-sloped zero crossings of the HeNe fringes, and this triggers sampling of the infrared (IR) fringes. The IR fringes are digitized and stored in a computer in less than one second. The IR interferogram is equal to the Fourier transform of the product of the SFS spectrum and the complex field reflection coefficient of the FBG [6,7].

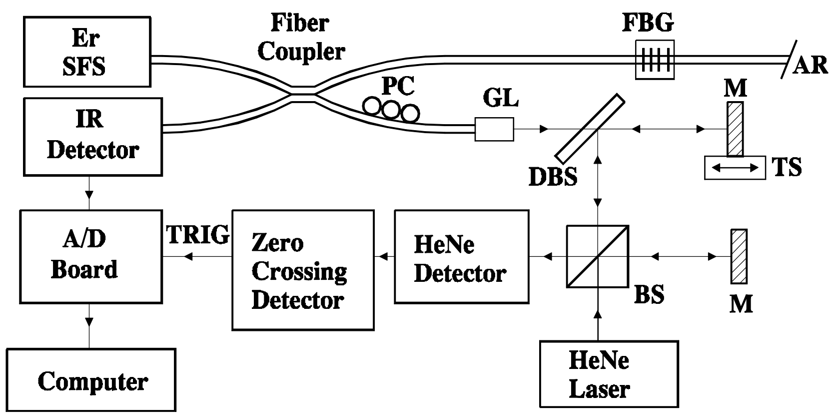

Fig. 1. Diagram of low-coherence interferometer. AR = antireflection (index-matching) gel; BS = beamsplitter; DBS = dichroic beamsplitter; GL = grin lens; M = mirror; PC = polarization controller; TS = translation stage.

The dispersion is calculated from the sampled IR interferogram as follows. We pad the ends of the interferogram with zeros in order to increase the wavelength resolution of our result and to obtain an array length of 2^N. Then we compute the Fourier transform of the padded interferogram. The group delay is obtained by numerically differentiating the phase of the Fourier transform. This process takes less than 60 s for a 2^{18} point interferogram.

The grating's power reflectance is calculated from the magnitude of the Fourier transform of the interferogram. This magnitude is equal to the product of the power spectrum of the SFS and the magnitude of the grating's complex field reflection coefficient. We normalize by the power spectrum of the SFS and square the result to obtain the grating's power reflectance. This is similar to Fourier-transform spectrometry, which is used to determine the power spectrum of a source. However, in this case, the spectral features of interest are determined not by the interferometer's source, but rather by a wavelength-selective reflector in one arm of the interferometer. Therefore, rather than yielding the

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power spectrum, our measurement yields the FBG's field reflection coefficient, and from that we obtain the power reflectance.

3. Experimental results

We used our low-coherence interferometer to measure the dispersion of a broadband, chirped FBG. This FBG had a 3 dB bandwidth of 14.8 nm, a center wavelength of 1551 nm, and a reflectance of 95%. We padded this FBG's interferogram with zeros to obtain an array length of 2^{18}, which corresponds to a wavelength resolution of 14 pm. The results are shown in Fig. 2. In the low-coherence measurement, the dispersion of the grating's fiber pigtail can be canceled using an equal length of identical fiber in the reference arm. Therefore, the measurement yields only the dispersion of the FBG plus the background dispersion, which is the sum of the dispersion of the grin lens, the dichroic beamsplitter, the air path, and the fiber length difference between the two fiber arms. Previous measurements have shown that the interferometer's background dispersion is very small (<11 fs/nm) and can be neglected compared with typical FBG dispersion [8].

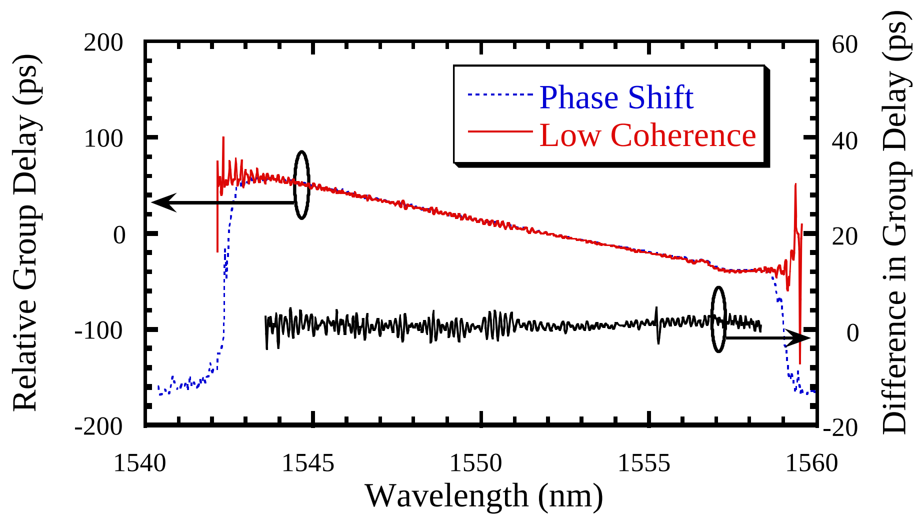

Fig. 2. Comparison of group delay obtained from low-coherence interferometric and modulation-phase shift measurements. The difference between the modulation-phase shift and low-coherence results over the grating's 3 dB bandwidth is also shown.

As a first-order estimate of the accuracy of the low-coherence results, we also measured the dispersion of this FBG with a modulation-phase shift measurement system [5] at a wavelength resolution of 15 pm. The modulation-phase shift measurement yields the sum of the FBG's dispersion and the dispersion of the grating's fiber pigtail. Therefore, we had to subtract the fiber's dispersion from our modulation-phase shift results. In order to accurately determine the fiber's dispersion, we started with equal lengths of fiber on both sides of the grating. After measuring the total dispersion from both launch directions with the modulation-phase shift system, we were able to determine the fiber's dispersion from the difference in the slopes of the two launch directions. We subtracted the fiber's dispersion from the modulation-phase shift measurements and plotted the resultant FBG group delay in Fig. 2. Also shown in Fig. 2 is the difference in group delay between the modulation-phase shift and low-coherence results over the grating's 3 dB bandwidth. Comparing the modulation-phase shift and low-coherence interferometric results shows an rms difference of 1.5 ps over the 3 dB bandwidth of the FBG reflection spectrum.

We also measured the power reflectance spectrum of a narrowband FBG. This FBG had a nominal center wavelength of 1552.9 nm, a bandwidth of 0.51 nm, and a reflectance of 99.99 %. We padded the interferogram with zeros to a total length of 2^{19}, which corresponds to a wavelength resolution of 7.2 pm. We calculated the spectral reflectance of this grating from the interferogram, and the result is shown in Fig. 3. Also shown in Fig. 3 is the spectral reflectance measured by scanning a tunable laser and monitoring the power reflected by the grating as a function of wavelength. Our tunable laser system includes a bandpass filter with a FWHM of 1.5 GHz to reduce the contribution of the laser's spontaneous emission to the measured reflectance. Therefore, in the absence of time-averaged thermal variations in the FBG reflection spectrum, the dynamic range of our tunable laser measurement is approximately 64 dB. However, in this particular case, the low-coherence results have more than twice the dynamic range of the tunable laser results. This is attributed to the fact that this grating does not have an athermal package and instead is mounted in a thermoelectric cooler (TEC). This TEC allows temperature variations of up to 1°C. In the tunable laser measurement, the reflectance at each wavelength is averaged over 10 s to improve the signal-to-noise ratio, and temperature-induced changes in the grating's reflection spectrum during this time wash out the spectral nulls. The low-coherence interferometric measurement obtains the entire spectrum in less than one second and is therefore immune to slow temperature changes in the TEC. This illustrates a key advantage of the low-coherence interferometric measurement, which is speed. The results of Fig. 3 agree to better than 25 pm and could be improved with either an athermal package or better temperature control.

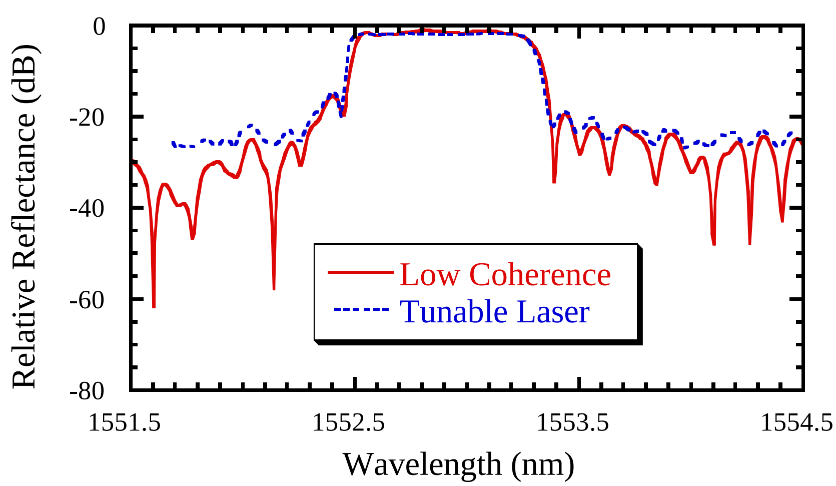

Fig. 3. Comparison of reflectance spectra measured with low-coherence interferometry and with a tunable laser system.

4. Conclusions

We have demonstrated low-coherence interferometric measurements of FBG dispersion and spectral reflectance. We have shown our dispersion results agree with the conventional modulation-phase shift results to within 1.5 ps rms, and we have shown that the wavelength of our spectral reflectance results agree with a tunable laser measurement to better than 25 pm. Previous measurements have shown repeatability better than 1 ps in the measurement of

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FBG dispersion [8]. A key advantage of this measurement method is its speed; dispersion and spectral results are obtained in less than one minute, compared with three hours to obtain dispersion, and one hour to obtain the spectral reflectance from conventional measurements. Therefore, the low-coherence interferometric measurement is less prone to errors resulting from temperature-induced grating changes and instrumental drift. We are currently investigating the effects of noise on group delay resolution, and we are analyzing the effects of systematic errors.